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THE KAMAN AIRCRAFT CORPORATION

BLOOMFIELD, CONNECTICUT

U. S. A.

REPORT NO. G-62

INTERIM ENGINEERING REPORT ON BASIC PERFORMANCE OF NON-POWERED, TETHERED LIGHTER-THAN-AIR VEHICLES FOR ANTENNA SUPPORT

CONTRACT AF 30(602)-675

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PART I

A. PURPOSE

For certain operations undertaken by the USAF, it appears desirable to be able to erect a low frequency vertical antenna rising to altitudes beyond that where conventional, ground-supported tower structures are feasible. In addition, the antenna should be portable, simple to erect in the field, and perhaps expendable.

The answer to the specifications noted may be a lighter-than-air vehicle supporting a cable or system of cables to serve at once as antennae and tethering lines. The ultimate configuration would result from study of the characteristics of two principal components, the cables or antennae and the supporting vehicle, considering those variables which will have a significant effect on satisfactory performance in the light of the requirements.

B. GENERAL FACTUAL DATA

1. Contributing Technicians

William E. Blackburn - Aerodynamicist, Bachelor of Aeronautical Engineering - Rensselaer Polytechnic Institute - Three years of experience at Kaman Aircraft Corporation.

Edith J. Polleys - Aerodynamicist - Bachelor of Arts, New York University - Seven years experience at Chance Vought Aircraft; Three years experience at Kaman Aircraft Corporation; Formal Engineering Training, eight months at Chance Vought Aircraft.

Lorraine A. Stisitis - Computer, One year experience at Pratt & Whitney Aircraft as billing machine operator; Six months computer experience at Kaman Aircraft Corporation on desk-type calculator.

ANALYSIS OF

2. References

1. Study of Tethered Airborne Antenna Support Vehicles - Description of Supplies or Services to be Furnished; Purchase Request continuation sheet for Purchase Request No. 339251, dated 5 February 1953.

2. Diehl, Walter Stuart, "Engineering Aerodynamics", The Ronald Press Company, New York, Revised Edition, Copyright 1936.

3. Johnson, J. M., "Balloon Engineering Design Manual", General Mills, Inc., ATI 179-857, 17 December 1951.

4. Scholkemeier, F. W., "Six-Component Measurements on a Balloon with Two Various Tails", translated German Technical Report ATI 25-416, 20 April 1943.

5. Warner, Edward P., "Airplane Design", Mc-Graw-Hill Book Company, Inc., New York and London, 1936.

6. Wald, Quentin, "Interim Engineering Report on An Analysis of the Forces in a Flexible Cable Subject to Wind and Gravity", Kaman Aircraft Report No. G-61, dated April 5, 1954.

3. **Symbols**

C_A = C_D = $\frac{\text{drag}}{q\ V^{2/3}}$, drag coefficient

C_L = C_W = $\frac{\text{lift}}{q\ V^{2/3}}$, lift coefficient

D = aerodynamic force in the direction of the relative wind, pounds

F_B = resultant buoyant force of gas, pounds

K_A = ratio of balloon surface area to the square of the diameter for spherical balloons

K_S = ratio of balloon seam length to the diameter for spherical balloons

K_V = ratio of balloon volume to the cube of the diameter for spherical balloons

L = aerodynamic force in a direction perpendicular to the relative wind, pounds

S = characteristic area, square feet

S_s = surface area, square feet

T_X = balloon reaction in a horizontal direction, pounds (usually net horizontal component of cable tension)

T_Y = balloon reaction in a horizontal direction, pounds (usually net vertical component of cable tension)

U = wind velocity in the free stream, feet/second

V = balloon volume, cubic feet

W = balloon deadweight, or the all-up weight excluding the weight of the gas, pounds

W_E = total weight of balloon envelope, pounds

W_p = weight of payload (instruments, etc.), pounds

W_S = total weight of balloon reinforcing tapes, pounds

d = balloon diameter, feet

Δh = vertical displacement of balloon from equilibrium

l = balloon length, feet

l_s = balloon seam length, feet

q = dynamic pressure of air, pounds/square foot

ΔS = horizontal displacement of balloon from equilibrium

w_e = unit weight of balloon envelope fabric, pounds/square foot

w_s = unit weight of reinforcing tapes, pounds/foot of length/inch of width

(x/L) = ratio of distance from nose to total length for a streamlined balloon

y = ratio of radius at any point to maximum diameter for a streamlined balloon

α = angle of attack of a streamlined balloon, degrees

δ_o = unit lifting force of gas at standard conditions at sea level, pounds/cubic foot

η = factor to allow for total weight of streamlined balloon over the basic envelope weight

θ = half-cone angle for spherical balloon, degrees

θ_p = elevation angle of top of cable measured from lower tether point

σ = square root of the ratio of mass density of air at altitude to mass density at sea level

τ = ratio of the length of a balloon to maximum diameter

C. DETAILED FACTUAL DATA

1. Introduction

It is the object of this report to present, in as general form as possible, the analysis of the forces on tethered, lighter-than-air vehicles with no power consuming thrust devices and to investigate the capabilities of such vehicles as supporting devices for a 2,500-foot high antenna system subject to conditions described in Case b, reference (1).

In order to establish the feasibility of non-powered lighter-than-air vehicles as antenna supports, it is simplest to examine the characteristics of such vehicles considered as captive balloons. Immediately, it becomes apparent that the total lifting forces and the drag forces are of primary importance. If it can be established that such a vehicle which will support a given cable configuration is of reasonable size so that handling and maintenance problems are not prohibitive, then other balloon characteristics may be considered. Therefore, the emphasis in this study is on the external forces which act upon a captive balloon flying under a given set of conditions.

2. External Forces on a Captive Balloon

Figure 1 shows a captive lighter-than-air vehicle in a steady wind blowing parallel to the ground. The balloon is assumed to be directionally stable so that the resultant forces and moments acting are coplanar. In addition, it is assumed that the system can be designed such that moment equilibrium may be obtained.

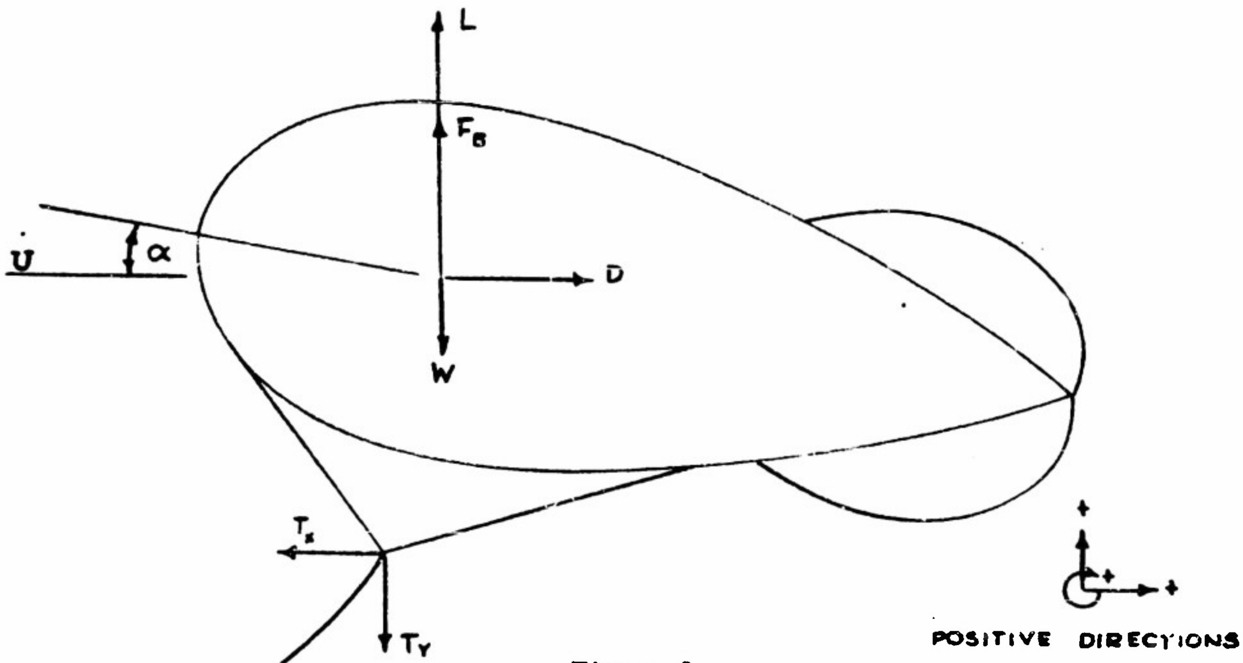


Figure 1

The resultant forces, aerodynamic lift and drag, the buoyant force, and the deadweight are shown acting through a common point. This is not the case in general, but, in studying only the nature of the forces, their distribution is of no concern.

(a) Spherical Balloon

Considering first a spherical balloon, it is immediately apparent that the aerodynamic lift is exempted from examination since it may be taken as zero. Only small lift variation, which may be neglected, is generated when the balloon departs from the exact spherical form. The aerodynamic drag of a sphere has been studied throughout a broad range of Reynolds numbers, and may be expressed analytically as

$$D = q\,S\,C_D \qquad (1)$$

where the drag coefficient, C_D, may be obtained from any suitable source such as reference 2 (see Figure 112) at the proper Reynolds number. If S is interpreted as the maximum cross-sectional area, equation (1) is written in terms of the diameter

$$D = \frac{q\,\pi\,d^2\,C_D}{4} \qquad (2)$$

In reference 3 a convenient method for determination of the volume of a full balloon of the shape shown in Figure 2 is presented.

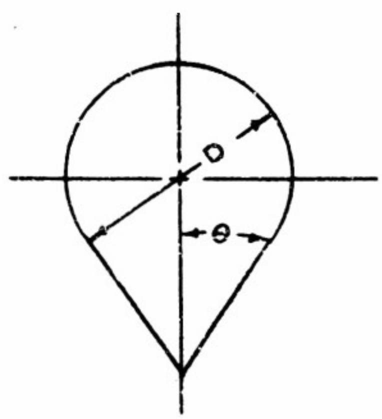


Figure 2

The volume is given in reference 3 as

$$V = K_V \; d^3 \tag{3}$$

where K_V is plotted in Figure A-30111-A, shown in this report as Figure 5, as a function of the cone angle 2 Θ. The buoyant force of the balloon is easily obtained at any desired altitude by multiplying the volume of the balloon by the unit lifting force of the particular gas used. Thus

$$F_B = \sigma \; \delta_o \; K_V \; d^3 \tag{4}$$

Reference 3 also provides a basis for estimation of the weight of the envelope, tapes, harness and other structural components for a given diameter balloon for various grades of fabric. The total surface area and seam length for the shape shown in Figure 2 is easily established in terms of the diameter for a given cone angle,

$$S_s = K_A \; d^2 \tag{5}$$

$$l_s = K_S \; d \tag{6}$$

Where K_A and K_S are obtained from figures A-30112-A and A-30113-A respectively of reference 3, shown in this report as Figures 6 and 7 respectively.

The weights of the envelope and seams are then

$$W_E = K_A d^2 \omega_e \tag{7}$$

$$W_s = K_S d \omega_s \tag{8}$$

The weight of the suspension harness for tethering and payload suspension is not rigorously established, but an estimate which increases the envelope and tape weight by two percent is sufficiently accurate from study of data presented in reference 3 on typical high altitude balloons.

The payload is a weight item controlled by specification and, hence, the deadweight of a lighter-than-air spherical balloon may be expressed as

$$W = (W_E + W_s)\, 1.02 + W_P$$

$$W = 1.02 \left(K_A d^2 \omega_e + K_S d \omega_s\right) + W_P \tag{9}$$

(b) Streamlined Balloon

When analyzing a streamlined balloon, it is necessary to include the aerodynamic lift contribution to the vertical force along with buoyant force. Because of the infinite variety of forms which might be considered for use as a streamlined balloon, it becomes more convenient to think in terms of the volume rather than the diameter as in the case of the Spherical Balloon. Accordingly, lift and drag are written

$$L = q V^{2/3} C_L \tag{10}$$

$$D = q V^{2/3} C_D \tag{11}$$

where the lift and drag coefficients are obtained from any suitable source such as reference 4.

The buoyant force is simply the product of the volume and the unit lifting force of the gas, thus

$$F_B = V \sigma \delta_o \tag{12}$$

A proper estimation of the deadweight of the streamlined balloon is complicated considerably by the infinite variety of shapes that might be used and by the fact that allowance must be made for the weight of stabilizing fins of variable size used in streamlined shapes. Fortunately, the envelope weight is small compared to other forces and relatively large errors here do not significantly affect the final results. However, as a basis for estimation, expressions found in reference 5 may be utilized. Equations (71) and (72) in reference 5 define the shape of a standard streamline form where equation (71) defines the shape for the front part of the balloon and equation (72) the rear part of the body:

$$(x/L)^2 + 0.16\,y^2 = 0.16 \qquad (-.40 \le x/L \le 0) \qquad (13)$$

$$(x/L)^2 + 0.0679\,y^2 + 0.2921\,y = 0.3600 \qquad (0 \le x/L \le .60) \qquad (14)$$

where the origin for x is located 40% aft of the nose. Rotating the curves about the x - axis results in a solid of revolution. A simple integration gives the volume in terms of the diameter and fineness ratio, l/d, as

$$V = .151\,\tau\,\pi\,d^3 \qquad (15)$$

From reference 5, equation (73), the wetted area is given as

$$S_s = 2.55\sqrt{Vl} + 1.22\,\frac{V}{d} \qquad (16)$$

Substituting for l in terms of the fineness ratio and d as defined by equation (15), equation (16) becomes

$$S_s = 3.84\,V^{2/3}\,\tau^{1/3} \qquad (17)$$

The weight of the basic envelope is then simply the product of the wetted area and the unit weight of fabric.

In addition to the basic envelope, other items to be considered are reinforcing tapes, suspension ropes, any valving arrangements, and, most important, the stabilising fins. The area, hence the weight, of the stabilizers is largely a matter of stability requirements, but because an approximation of the balloon weight to ten percent accuracy is needed for the purpose of this report, it seems justified to examine some model configurations to determine the surface area of fins for typical configurations. This model study permits determination of a factor, η , by which the basic envelope weight may be multiplied to account for the weight of fins, ropes, etc. The deadweight of the streamlined balloon may then be written

$$W = 3.84 \eta V^{2/3} \tau^{1/3} w_e + W_p \qquad (18)$$

3. Cable Reaction Forces, T_x and T_y, of a Captive Balloon

The force components, T_X and T_Y, represent the forces which must be supplied by the tethering cable to maintain force equilibrium along the vertical and horizontal directions for either the streamlined or spherical configuration.

The equilibrium of forces in the vertical and horizontal directions is written as (see Figure 1)

$$\Sigma F_x = D - T_X = 0 \qquad (19)$$

$$\Sigma F_y = L + F_B - W - T_y = 0 \qquad (20)$$

where positive forces are taken in the direction indicated by arrows in Figure 1, page 8.

For the spherical balloon, making proper substitutions for lift, drag, buoyant force, and deadweight, equations (19) and (20) become

$$T_X = \frac{q \pi d^2 C_D}{4} \tag{21}$$

$$T_Y = \sigma \delta_o K_V d^3 - 1.02 (w_e K_A d^2 + w_g K_g d) - W_P \tag{22}$$

Similarly, for the streamlined balloon

$$T_X = q V^{2/3} C_D \tag{21a}$$

$$T_Y = qV^{2/3} C_L + V \sigma \delta_o - 3.84 \eta V^{2/3} \tau^{1/3} w_e - W_P \tag{22a}$$

4. <u>Balloon Size Determination of Three Cable Tethering at 2500 feet</u>

A typical calculation is performed at this point to illustrate the method used to determine a balloon size for either a spherical or a streamlined captive balloon, helium-filled, in a 50 knot wind.

Given:

U = 50 Knots

W_P = 0

$\sigma \delta_o$ = .061 lb/ft^3 for helium at sea level

From the Table of Weights, reference 3

w_e = .0144 lb/ft^2 (Typical)

w_g = .0027 lb/ft/in (Typical)

(a) Resultant Forces on a Spherical Balloon

Assume $\theta = 60^\circ$

From reference 3

$K_V = .52628$

$K_A = 3.1579$

$K_S = 1.5976$

The Reynolds number is sufficiently high throughout an appreciable diameter range so that, from reference 2, Figure 112,

$C_D = 0.21$.

Then,

$$T_X = \frac{q\pi d^2 C_D}{4}$$

$$= \frac{(8.5)(\pi)(.21)(d^2)}{4}$$

$$= 1.4d^2$$

$$T_Y = \sigma\gamma_o K_V d^3 - 1.02\ (w_e K_A d^2 + w_s K_s d) - W_P$$

$$= (.52628)\ (.061)d^3 - 1.02\left[(.0144)\ (3.1579)d^2 + (.0027)\ (1.5976)d\right]$$

$$= .032d^3 - .046d^2 - .004d$$

The curve of vertical versus horizontal force is plotted in figure 4 for several diameters with no payload.

(b) Resultant Forces on a Streamlined Balloon

Assume the harness is designed to operate the balloon at the angle of attack for maximum L/D. From reference 4

$C_L = 0.114$

$C_A = 0.340$

at 15.1° angle of attack.

Also from reference 4

$$\tau = \frac{l}{d} = \frac{1272}{352.2} = 3.6$$

Then

$$T_X = q\, C_D\, V^{2/3}$$
$$= (8.5)\ (.114)\ V^{2/3}$$
$$= .97\ V^{2/3}$$

$$T_y = q\, C_L V^{2/3} + \sigma \delta_o V - 3.84\, \eta\, V^{2/3} \tau^{1/3} w_e - W_P$$
$$= (8.5)(.340)V^{2/3} + .061V - (3.84)(1.533)(2)(.0144)V^{2/3} - W_P$$
$$= 2.72\ V^{2/3} + .061V$$

where the envelope weight is assumed to be doubled by the addition of fins, etc., that is $\eta = 2.0$.

The curve of vertical versus horizontal force is plotted in Figure 4 for streamlined balloons of various volumetric capacities.

(c) <u>Resultant Forces on a Typical Cable Configuration</u>

The remaining curves appearing in Figure 4 represent the variation in cable tension components for typical three-cable configurations at various displacements from the origin which is located at the equilibrium position in space assumed by the balloon in zero wind. The points on these curves have been calculated using methods described in reference 6. The cable disposition is shown below in Figure 3

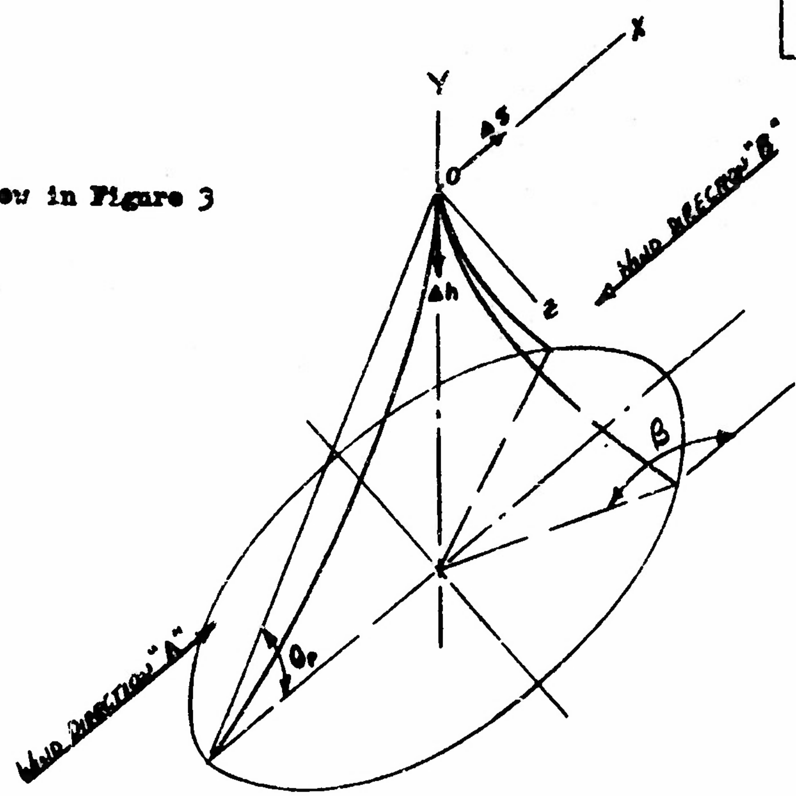


Figure 3

Data applying to each of three steel cables is listed below:

Initial cable sag, $\left(\frac{A}{L}\right)$ = .05

Cable diameter = .221 in.

Unit weight = .0833 lb/ft

Wind velocity, U = 50 knots

It is apparent, for a given cable configuration, that the balloon which will support it is determined by the intersection of the cable load curves with the balloon load curve, such as points A, B, C.

5. **Discussion**

It should be noted that the numerical results presented in this report represent typical configurations and should not be considered necessarily to represent the optimum without further study. However, as far as the vehicles are concerned, the parameters which are not specified but are subject, within limits, to design choice, are selected as being nearly representative of actual conditions. Therefore, it appears that no significant performance changes should be expected in the detail design of either a spherical or streamlined balloon.

The cable system, which must supply the reactions to vehicle loads, may be subject to a wider variation in the loads it produces depending upon the function of the cable, its orientation with respect to the wind, its initial sag, and its physical characteristics. It seems probable that a smaller, lighter cable than that chosen for illustration would lack sufficient tensile strength with a proper margin of safety, particularly for the gust condition of 87 knots.

Thus, as is made apparent in Figure 4, because of its extremely low ratio of total lift to drag forces in a 50 knot wind, a spherical balloon is unsuitable as an antenna support under conditions specified under Case B of reference (1). More generally, the superiority of the streamlined balloon over a spherical balloon for antenna-support purposes is so clearly indicated that spherical balloons do no warrant further consideration under any conditions.

In the case of a single cable configuration, Table III (d) shows that neither a spherical nor a streamlined balloon may be used as an antenna support under conditions described under Case B reference (1) because a single cable must be carried excessively far downwind before the tension has an upwind component which is, of course, required by a support vehicle with no external power source.

A streamlined balloon, because of its greatly reduced drag and its aerodynamic lift, appears satisfactory as an antenna support vehicle at least for a three-cable system. For a typical set of cable loads, Line A of figure 4, equilibrium of a streamlined balloon, the volume of which may be easily computed using equation (21a), is established when the balloon has moved approximately 35 feet downstream from the origin. The volume of the balloon is 35000 feet^3, which, for the chosen length-diameter ratio of 3.6, is 98 feet long and has a maximum diameter of 27 feet. The question may arise , after study of Figure 4, as to the reason for the choice of a balloon of this size when it appears that a smaller volume of 21,500 feet^3 could be utilized by allowing a drop of 50 feet in altitude so that the intersection of the cable curve, Line C, with the streamlined balloon curve occurs at point C. It is readily seen, however, that the direction of the wind has a significant effect on the cable loads. This becomes apparent from comparison of Line A and Line A, (Figure 4) where only the wind direction is changed from one case to another. For Line A where the wind is blowing along one cable with the other two symmetrically displaced downwind (See Figure 3, wind direction A) the resulting loads on a balloon are lower than for the case Line A, where the wind is shifted 180°. Making a conservative allowance for this fact coupled with a 50 ft drop in altitude leads to the choice of a 35,000 ft^3 streamlined balloon to limit horizontal displacement in a fifty knot wind to less than 200 feet.

It should be emphasized here that the specific task the balloon is required to perform determines its size and no general statement which is perfectly valid for all cable systems should be made, aside from the obvious fact that a streamlined balloon is superior in every case to a spherical shape. It is clear, however, that when cable loads are completely established, no difficulty is to be expected in selecting a satisfactory balloon for a supporting vehicle.

D. CONCLUSIONS

(1) A satisfactory method is established to determine the aerodynamic characteristics of lighter-than-air non-powered captive balloons of both spherical and streamlined shape.

(2) The ratio of vertical to horizontal forces does not significantly change for a balloon of given volume under given wind conditions for small changes in detail design parameters.

(3) Spherical balloons may be eliminated from consideration as airborne antenna support vehicles under conditions of Case B, reference (1).

(4) For a single cable configuration, it appears that neither a streamlined nor a spherical balloon would be a satisfactory support under conditions listed under Case B, reference (1).

(5) A streamlined balloon, having a volume of 35,000 ft^3, a length of 98 feet, and a diameter of 27 feet would be a satisfactory antenna support vehicle under conditions listed under Case B, reference (1).

PART II

TABLE I

RESULTANT FORCES ON A SPHERICAL BALLOON IN A 50 KNOT WIND

DIAMETER FT	VOLUME FT^3	VERTICAL FORCE LB	HORIZONTAL FORCE LB
0	0	0	0
10	526	27	140
20	4210	238	560
30	14210	823	1260
40	36800	1974	2240
47	54640	3221	3093

TABLE II

RESULTANT FORCES ON A STREAMLINED BALLOON IN A 50 KNOT WIND

VOLUME FT^3	VERTICAL FORCE LB	HORIZONTAL FORCE LB
0	0	0
10000	1323	450
30000	4456	937
60000	7829	1487

TABLE III (a)

RESULTANT CABLE REACTIONS IN A 50 KNOT WIND

Three steel cables at 120° to each other

$\theta_p = 60°$ (each cable)
Wind direction A (See figure 3 Page 18)
Cable diameter = .221 inches
Cable weight = .0833 lb/ft

VERTICAL DISPLACEMENT Δ_y = Ft	HORIZONTAL DISPLACEMENT Δ_x = Ft	VERTICAL FORCE Lb	HORIZONTAL FORCE Lb
0	0	3083	- 556
	30	3994	264
	32	4316	446
	36	5757	1332
-25	0	2127	- 595
	30	2233	- 424
	60	2657	- 73
	75	3780	666
-50	0	1701	- 604
	100	2319	- 21
	110	2728	261
	118	3704	903
	119.5	4163	1201

TABLE III (b)

RESULTANT CABLE REACTIONS IN A 50 KNOT WIND

Three steel cables at 120° to each other
θ_p = 60° each cable
Wind direction "B" (See Figure 3, Page 18)
Vertical displacement, Δ_y = 0
Cable diameter = .221 inches
Cable weight = .0833 lb/ft

HORIZONTAL DISPLACEMENT Δ_x - Ft	VERTICAL FORCE T_y - Lb	HORIZONTAL FORCE T_x - Lb
0	3049	- 318
30	3875	144
60	5351	680
64	5970	900
66	6447	1061

TABLE III (c)

RESULTANT CABLE REACTIONS IN A 50 KNOT WIND

Three steel cables at 120° to each other
θ_p = 75° each cable
Wind direction A (See figure 3, Page 18) Vertical displacement, Δ_y = 0'
Cable diameter = .221 inches Cable weight = .0833 lb/ft

HORIZONTAL DISPLACEMENT x = Ft	VERTICAL FORCE T_y - Lb	HORIZONTAL FORCE T_x - Lb
0	3412	-653
30	3646	-474
50	4364	-198
60	5906	288

TABLE III (d)

RESULTANT CABLE REACTIONS IN A 50 KNOT WIND

Single steel cable
θ_p = 90^0
Cable diameter = .383 inches

Length = 2500 Ft
Cable weight = .25 lb/ft

VERTICAL DISPLACEMENT Δh - Ft	HORIZONTAL DISPLACEMENT Δx - Ft	VERTICAL FORCE T_y - Lb	HORIZONTAL FORCE T_x - Lb
51	500	2408	- 3
100	700	2449	-206
209	1000	2427	-521

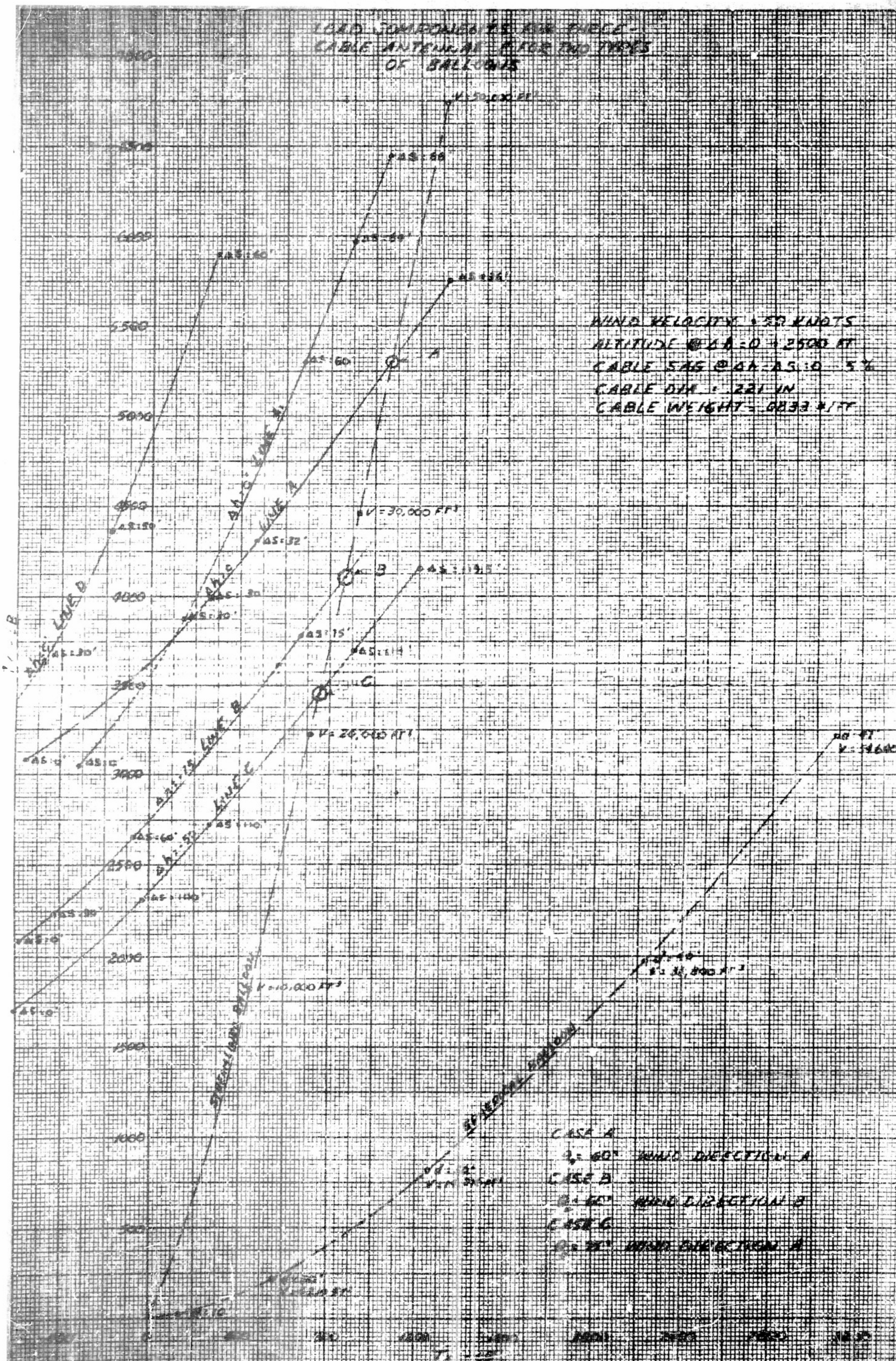

LOAD COMPONENTS FOR THREE-
CABLE ANTENNAE FOR TWO TYPES
OF BALLOONS
WIND VELOCITY = 50 KNOTS
CABLE DIA = .221 IN
CASE A
CASE B
CASE C
V = 30,000 FT³
V = 26,000 FT³
V = 10,000 FT³
STREAMLINED BALLOON
SPHERICAL BALLOON

FIGURE 4

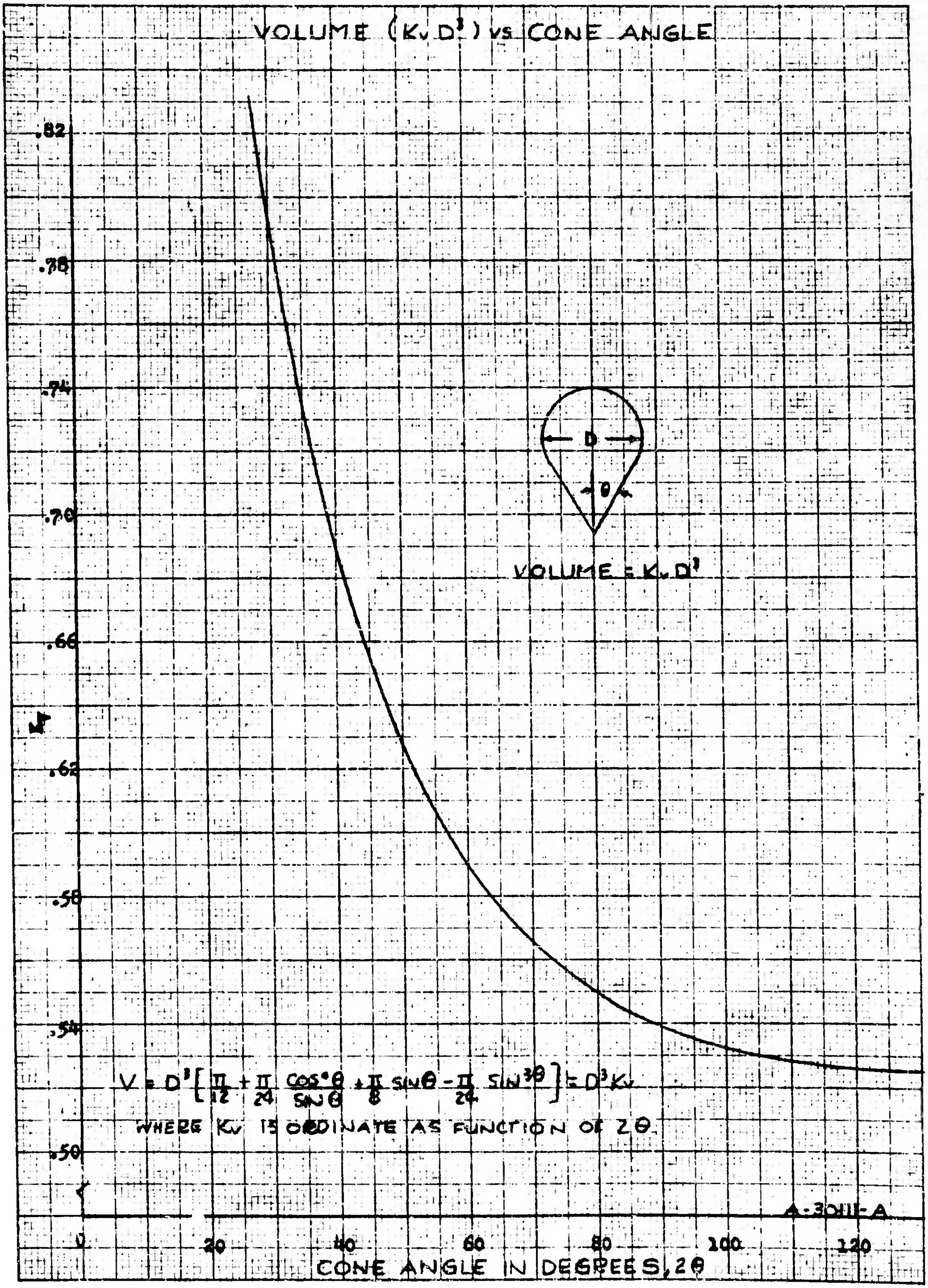
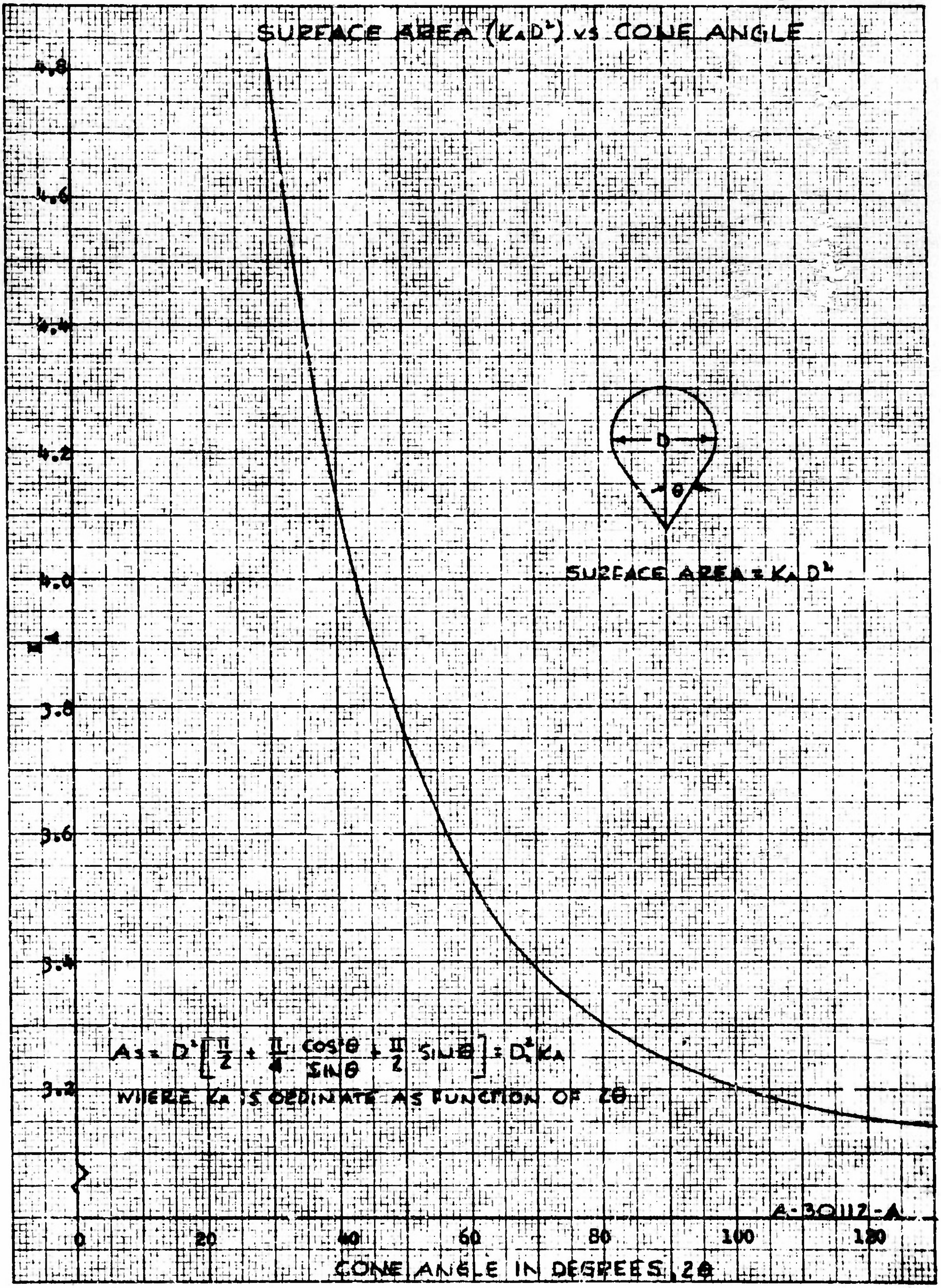

VOLUME ($K_v D^3$) vs CONE ANGLE
.82
.78
.74
.70
.66
.62
.58
.54
.50
K_v
D
θ
VOLUME = $K_v D^3$
$V = D^3\left[\frac{\pi}{12} + \frac{\pi}{24}\frac{\cos^4\theta}{\sin\theta} + \frac{\pi}{8}\sin\theta - \frac{\pi}{24}\sin^3\theta\right] = D^3 K_v$
WHERE K_v IS ORDINATE AS FUNCTION OF 2θ
A-30111-A
0
20
40
60
80
100
120
CONE ANGLE IN DEGREES, 2θ

Figure 5



359-11 KEUFFEL & ESSER CO.
10 × 10 to the ½ inch, 5th lines accented.
MADE IN U.S.A.

Figure 6

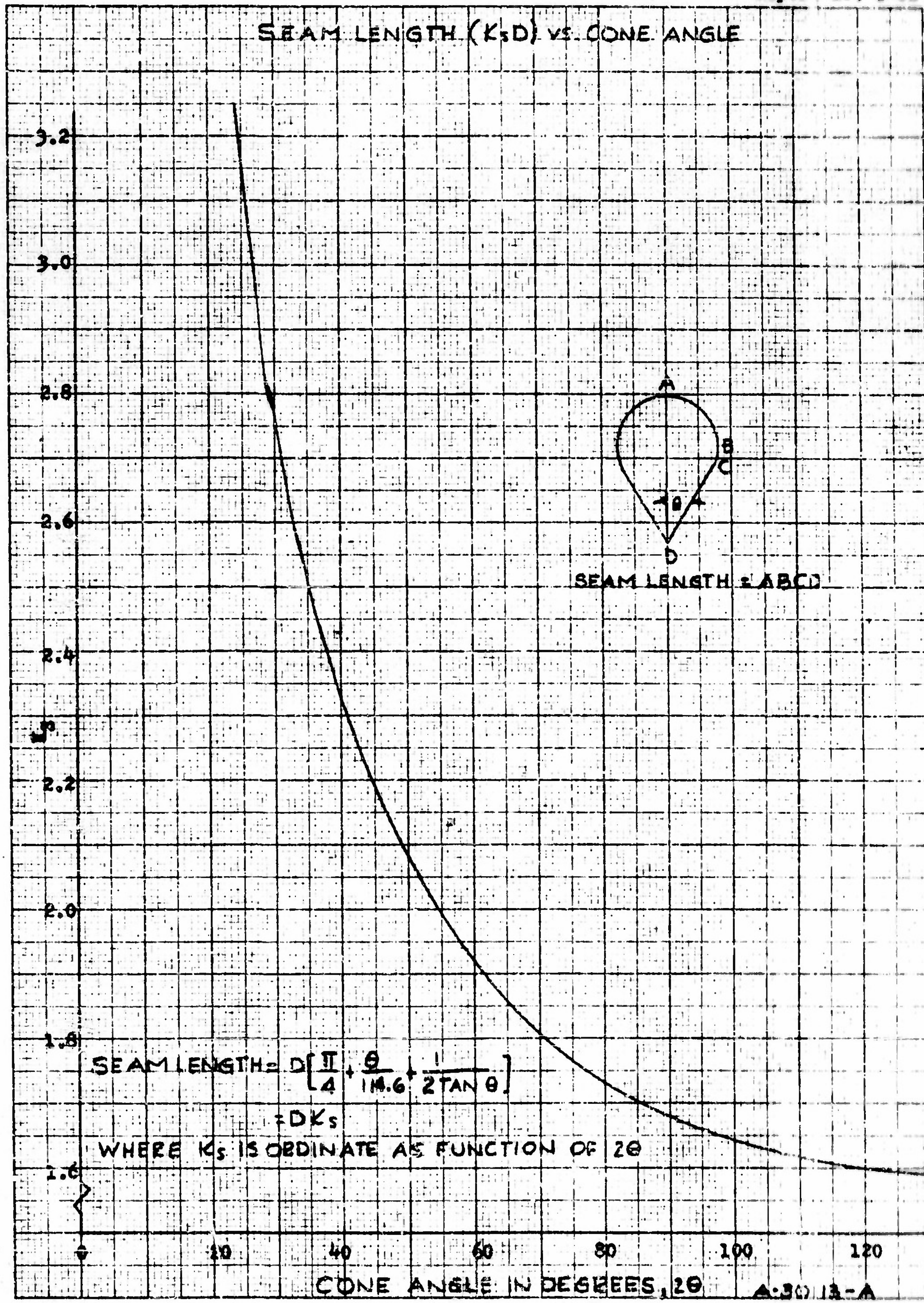


Figure 7

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